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Present status and prospects of photovoltaic technologies in Japan

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Abstract

This paper reviews the present status of research, development and manufacturing for photovoltaics (PV) in Japan based on the Japanese New Sunshine Program conducted by the Ministry of International Trade and Industry (MITI) and the New Energy and Industrial Technology Development Organization (NEDO). In particular, the status of research and development on high-efficiency and low-cost crystalline silicon, thin-film silicon and Group II–VI compound solar cells and modules, and super high-efficiency Group III–V compound solar cells, is presented. In addition, Japanese government programs to promote solar houses, wherein 18,000 PV systems were installed on Japanese houses in 1999, are also demonstrated. Future prospects for PV technologies, such as silicon material, thin-film and module technologies, concentrator systems and new application fields, are discussed. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Solar photovoltaic (PV) power generation technology is one of the most promising renewable energy technologies for the 21st century because of its possibility for solving environmental problems and limited sources of energy. Fig. 1 shows an installation scenario [1] of total energy in Japan. Although the installation ratio of PV energy to total energy planned in the year 2030 is only 10%, the introduction

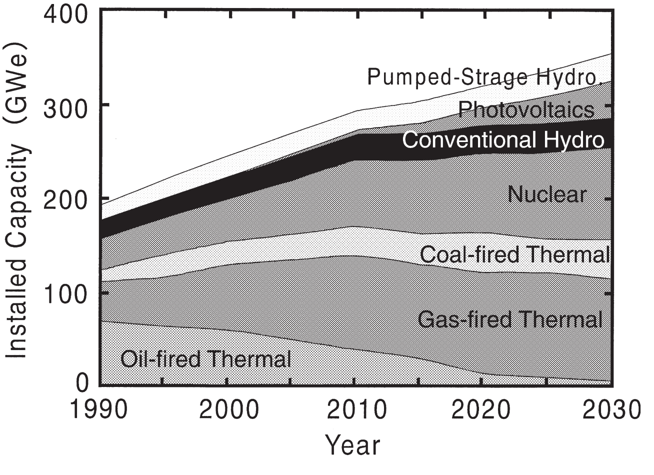


Fig. 1. An installation scenario of total energy in Japan.

of PV systems will be carried out continuously. In fact, the total amount of new energy that should be introduced by fiscal year (FY) 2010 was addressed in “Policy-Target of Alternative Energy Supply” issued in 1998, which declared that the solar PV contribution should be expected to be 5000 MW cumulative (or the equivalent of 1.220×10^9 litres of oil per year). Along with other kinds of renewable energy, the amount of energy expected to be saved by introducing PV systems will make a certain contribution to the 6% reduction in CO_2 emission that Japan has to achieve as declared in the COP3 Kyoto Protocol.

To realize this expectation of PV introduction, reducing the installation cost of PV systems should be most effective. The basic strategy to realize this expectation of PV introduction is to make the production cost low enough so that roof-top PV power generation systems will be advantageous even based on short-term household economics. Fig. 2 shows the number of installations of PV power generation systems for residential use in Japan. A Japanese government program to promote solar houses started in FY 1994. In 1999, 18,000 PV systems were installed on Japanese houses.

In addition, the PV market continues to grow with global production of over 200 MW_p in 1999. Therefore, PV solar energy conversion is expected to become a matter of great interest and importance.

2. Overview of Japanese government PV programs

The target for PV system introduction is 400 MW by year 2000 and 5000 MW by 2010 according to the Total Primary Energy Supply Outlook prepared in June 1998 by the Advisory Committee for Energy [an advisory body of the Ministry of International Trade and Industry (MITI)]. PV technology development is mainly being carried out in a national R&D program called the New Sunshine Project and

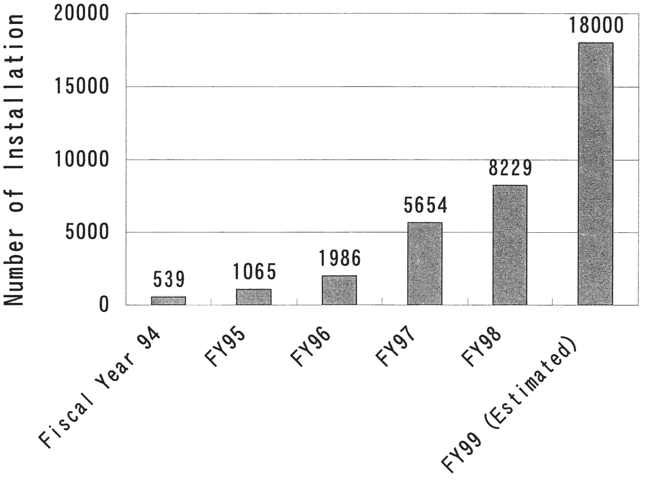


Fig. 2. Number of installations of PV power generation systems for residential use in Japan.

some other R&D programs. Fig. 3 shows the trend of the budget for PV in the Japanese National Program. The Japanese government has established some promotional programs such as financial subsidies for Residential PV Systems and the PV Field Test Program to demonstrate PV installations. The data collected from these programs are useful for analysis of the cost and performance of systems. Concerning residential PV systems, cost reduction is now achieving the level of 1 million Japanese Yen (JPY) per kW in the market, while further reduction is strongly required to obtain economical viability.

2.1. PV R&D program (Japanese New Sunshine Program)

A Japanese R&D program, named the Sunshine Project, to promote the introduction of “new energy” — including solar energy (both thermal and photovoltaic), geothermal energy and the utilization of hydrogen as an energy carrier — was started in FY 1974. In the meantime, the importance of the global environment became more and more pronounced. A major revision was done to unify these energy-related programs and a new phase of national R&D was installed as the New Sunshine Program in FY 1993. This new program places prime emphasis on the co-operative resolution of sustainable growth, the global environment and energy supply. PV is expected as one of the key technologies to achieve the ambitious goal of the New Sunshine Program.

The New Sunshine Program [2] aims at promoting a comprehensive, long-term R&D program that extends to 2010. The R&D policies are designed to encourage the development of technologies that facilitate the start of a “favorable circle” enabling mass production at a cost low enough to spur further demand, which improves the scale of economy for production and a sustainable PV market in consequence. The target by 2000 is to develop technology that can realize PV electricity at a cost equal to conventional electricity charges, i.e., 20–30 JPY/kWh, which is the same cost level necessary for large-scale power generation.

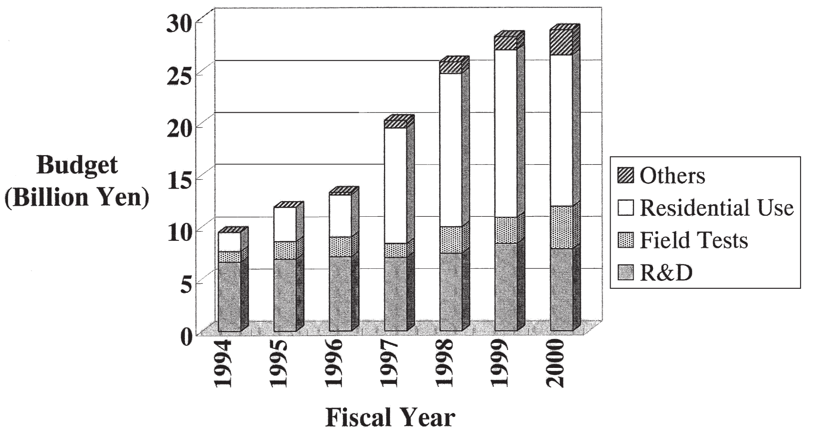


Fig. 3. The trend of the budget for PV in the Japanese National Program.

Fig. 4 shows a schedule for the development of solar cell manufacturing technology in Japan. The first step in the development of solar cells was mainly devoted to polycrystalline silicon (poly-Si) solar cells. Bulk-type polycrystalline silicon technology has already achieved the target of the New Sunshine Project and a conversion efficiency of over 17% for a 225 cm^2 cell (15 cm×15 cm) was realized. The efficiency of commercially available modules has been between 13% and 15%. Developments in the production technology of solar-grade silicon (SOG-Si) feedstock, continuous electromagnetic casting and high-productivity slicing are also being carried on. In addition, a task to increase the efficiency and reduce the cost of poly-Si cells was started in 1999 with the expectation of having an immediate contribution to existing production lines.

The tandem structure of an amorphous silicon (a-Si) cell with an area of 1 cm^2 recorded a stable efficiency of 11.5%, and the efficiency of a-Si sub-modules (30 cm×40 cm) has improved year by year, achieving a stable efficiency of 9.5% — near the target of more than 10% in efficiency (with a 90 cm×90 cm module). To realize a low-cost, high-performance and stable solar cell, an a-Si/poly-Si hybrid thin-film structure is being developed with the target of a stable efficiency of 14% by year 2000.

Cadmium telluride (CdTe) technology has been focused on the development of large-area, thin-film module production. For a 5413 cm^2 sub-module with a CdS layer of 0.05 μm and a CdTe layer of 3.5 μm, the efficiency of 10.6% was achieved. A 1 cm^2 thin film of CdTe recorded 16.0% efficiency. The result shows the possibility of 13% efficiency target on large-area modules (60 cm×90 cm) by 2000. $CuInGaSe_2$ (CIGS) cells achieved an efficiency of 18.5% with 0.96 cm^2 and 12.48% with 859.5

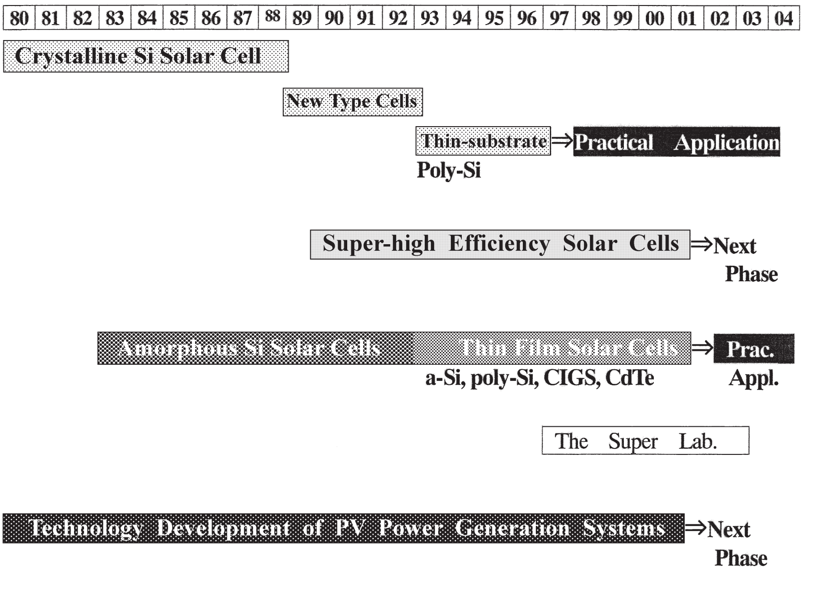


Fig. 4. Schedule for solar cell manufacturing technology development in Japan.

cm^2, while the target efficiency by 2000 is 16% with 10 cm×10 cm and 13% with 30 cm×30 cm. The cost target for thin-film solar cell modules made from a-Si-based thin films, CdTe and CIGS thin films, to be achieved by FY 2000 under the New Sunshine Program, is 140 JPY/W_p for a production size of 100 MW_p/year.

A cell with world-record efficiency (33.3%) was previously fabricated in a mechanically stacked InGaP/GaAs//InGaAs triple junction of 1 cm^2 area in 1997. The targets by FY 2000 are 30% on germanium and 25% on silicon, both in 5 cm×5 cm monolithic cells. An efficiency of 30.9% has already been obtained for a 1 cm^2 InGaP/GaAs dual-junction cell on a germanium substrate.

With regard to PV systems technology, research and development on building-integrated PV modules is being carried out, that can be integrated with roof-tops for residential houses and facades for buildings. These systems have the economic advantage of saving mounting costs and added function as a building material.

The power quality, safety and stability of the utility grid in which PV systems are interconnected in high density are being analyzed and evaluated. In addition, highly reliable islanding prevention methods are being studied and suppression measures of harmonic distortion generated from inverters are being developed. Technology for the value-added PV application is studied. This includes additional functions such as voltage stabilization, reactive power compensation and harmonics reduction, in order to enhance the benefits for both consumers and electric power utilities.

2.2. Subsidy program for residential PV systems (Residential PV System Monitoring Program)

With respect to the dissemination and promotion of PV systems, the Residential PV System Monitoring Program was established in 1994. In this program, half of the installation costs was subsidized by the Government with the aim of supporting the installation of PV systems on houses. In 1997, the Residential PV System Monitoring Program was expanded to the Subsidy Program for Residential PV Systems. As of 1997, however, the Government subsidized one-third of the installation costs in the Subsidy Program for Residential PV Systems. PV systems were installed on 17,473 houses between FYs 1994 and 1998. The average capacity for a house is 3.7 kW, the output approximately 991.2 kWh. About 54% of the generated power was bought back by electric power companies. As shown in Fig. 2, PV systems were installed on 18,000 houses in FY 1999 (April 1999–March 2000). Fig. 5 shows the price reduction and the target price level of 3 kW PV systems for residential houses in Japan by 2000 and 2010.

The housing industry has begun to promote the PV integrated residential house in earnest. The market for residential PV systems is expected to be self-sustainable in the near future, provided the reduction of installation costs can be achieved to a reasonable extent.

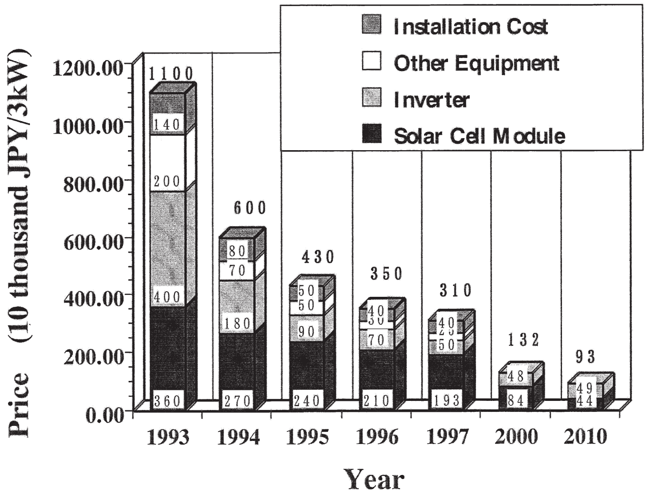


Fig. 5. The price reduction and the target price level of 3 kW PV systems for residential houses in Japan by 2000 and 2010.

2.3. Field Test Program

With respect to the dissemination and promotion of PV systems, the PV Field Test for Public Facilities Program was established in 1992. In 1997, the PV Field Test for Public Facilities Program was broadened mainly to cover PV installations to office buildings and industrial applications. As of 1997, the Government subsidized half of the installation costs in the PV Field Test for Public Facilities Program. The PV Field Test for Public Facilities Program completed successfully in FY 1997. The number of installations under the program totaled 186 systems and 4900 kW. The PV Field Test for Public Utilities Program was expanded and renamed the “PV Field Test for Industrial Use” program in FY 1998.

Fig. 6 shows the trend of accumulated PV installation capacities in Japan.

3. Present status of research and development of PV in Japan

In this section, the present status of R&D on high-efficiency and low-cost crystalline Si, thin-film Si and Group II–VI compound solar cells and modules, and super high-efficiency Group III–V compound solar cells, is presented.

Table 1 shows the present status, characteristics and application areas of various solar cells. Silicon has been and continues to be the foundation of the PV industry. The material is abundant, comprising about 20% of the earth’s crust. Bulk-type crystalline silicon cells such as single-crystal and poly-crystal Si cells have been mainly used for terrestrial cells as the first-generation cell. Amorphous silicon cells are expected as the second-generation terrestrial solar cell because of the possibility of low cost.

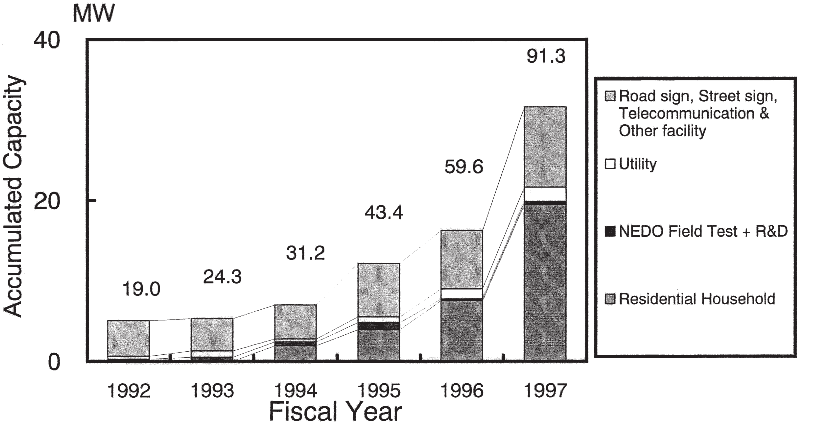


Fig. 6. The trend of accumulated PV installation capacities in Japan.

Table 1
Present status, characteristics and application areas of various solar cells[a]

Generation	Solar cell materials	Conversion efficiency (%)	Radiation resistance	Reliability	Cost	Application area
I	Single-crystal Si	24.7	△	●	○	Terrestrial, Space
	Poly-crystal Si	19.8	△	●	○	Terrestrial
II (Thin Film)	Amorphous Si	14.5	△	△	●	Consumer, Terrestrial
NEXT (Advanced Thin Film)	Poly-Si thin film	16.0	△	○	●	(Terrestrial)
	II-VI compound thin film	18.8	●	○	○	(Terrestrial)
	Concentrator tandem	32.6	●	○	○	(Terrestrial, Space)
Space	GaAs	25.7	○	●	△	Space
	InP	22.0	●	●	△	Space
	Tandem	33.3	○	●	△	Space
New Materials	TiO_2	11.0	?	△	●	(Terrestrial)
	Organic	2.0	?	△	●	(Terrestrial)
	Carbon	3.3	?	○	●	(Terrestrial)

[a] ● Excellent; ○ Good; △ Fairly good.

As the next-generation terrestrial solar cells, poly-crystal Si thin-film cells, II–VI and chalcopyrite compound poly-crystal thin-film cells, and concentrator tandem cells are expected. Dye-sensitized cells using TiO_2, organic cells and carbon cells are being studied as new types of cell using new materials. Group III–V compound single-crystal cells such as GaAs, InP and InGaP/GaAs tandem cells are being used for space applications because of their high efficiency and radiation tolerance.

3.1. High-efficiency and low-cost crystalline Si solar cells

Today, laboratory single-crystal Si cells with efficiencies exceeding 24% have been confirmed, and module efficiencies more than 20% have been demonstrated. Under the New Sunshine Program, the first step in the development of solar cells was mainly devoted to polycrystalline Si solar cells. Fig. 7 shows chronological improvements in the conversion efficiencies of large-area single-crystalline and polycrystalline Si solar cells at the laboratory scale in Japan. The maximum efficiency achieved for cast polycrystalline Si cells is 17.1% for a 225 cm^2 cell. At present, R&D on polycrystalline Si solar cells has already graduated from the New Sunshine Program and has shifted to large-scale production. The efficiency of commercially available, bulk polycrystalline Si solar cell modules is between 13% and 15%.

Fundamental studies of high-efficiency crystalline Si solar cells have also contributed to the developments of high-efficiency and low-cost Si cells. This means that the important issue for further improvements in PV technologies is close co-operation of government, universities and companies.

From FY 1999, a new four-year R&D program [3] for polycrystalline Si solar cells has been restarted to make up the gap between the market and R&D directions. In the new R&D program, there are several R&D items and targets to be achieved

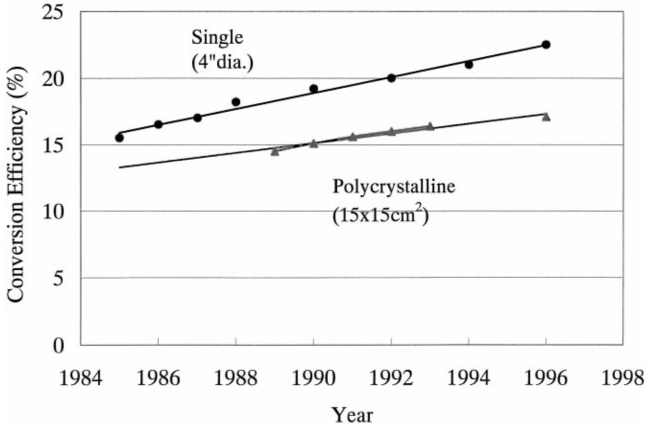


Fig. 7. Chronological improvements in conversion efficiencies of large-area single-crystalline and polycrystalline Si solar cells at the laboratory scale in Japan.

until FY 2002. Primary targets indicated in Table 2 are a very high cell efficiency of 20% and lower production cost of 147 JPY/W_p using a very thin substrate of 150 μm. These two targets are very ambitious to meet with the current electricity cost of conventional utility lines and also to compete with film-type approaches. To attain the targets indicated in Table 2, the following R&D subjects are expected to be promoted:

1. Technology development of very-high-quality cast ingot production to realize the cell efficiency of 20%. The development will be carried out by investigating the relation between crystal quality and cell efficiency in more detail.
2. Technology development of an advanced wire-saw slicing for very thin substrates. This will be performed by developing a thinner, more durable wire and fast slicing technology.
3. Development of high-efficiency cell fabrication technology to achieve 20% using the thin substrates. The high efficiency will be realized by fabricating sophisticated structures including light trapping, passivation of crystal defects in the bulk and surfaces, high-quality *pn* and back surface field (BSF) junctions, low-resistivity electrodes, etc.

Fig. 8 shows the problems to be solved for polycrystalline bulk-type Si cells. In order to improve their efficiency further, reduction in surface reflection, reduction in front- and rear-surface recombination, optical confinement structure, high-quality crystal growth, gettering of impurities and defects, and passivation of grain boundaries and defects are necessary. In order to reduce their cost, high-speed and large-volume SOG-Si production, high-speed and large-diameter crystal growth, development of slicing technology for thin-wafer fabrication of less than 150 μm, and high-speed, simple cell processing are necessary.

3.2. a-Si and thin-film Si solar cells

a-Si cells are expected as an ideal photovoltaic candidate. Their optical absorption characteristics validate the material's economy with thin films. In addition, thin films could be deposited on low-cost substrates in any dimension for large-scale production with low process energy.

Table 2
Outline of targets of a new four-year R&D program for polycrystalline Si solar cells in Japan

Item	Target
R&D period	FY 1999 to FY 2002
Substrate size	15 cm×15 cm
Substrate thickness	150 μm
Curf loss	150 μm
Cell efficiency	20%
Production cost	147 JPY/W_p (100 MW_p/year)

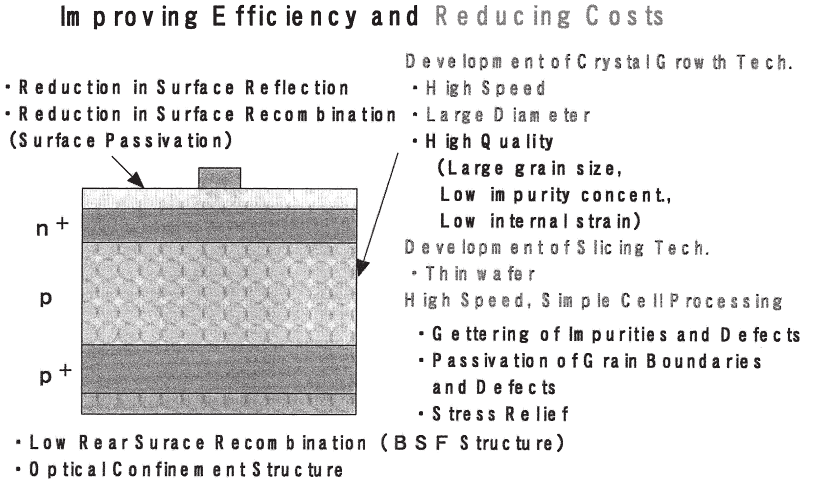


Fig. 8. Problems to be solved for polycrystalline bulk-type Si cells.

For PV applications, however, there are problems such as instabilities observed when exposed to light (the Staebler–Wronski effect) and demands for low-cost mass production as a power-generating technology.

The most important issue to improve the stabilized efficiency of a-solar cells is the development of fabrication techniques for high-quality intrinsic (i)-layers. For this purpose, the hydrogen dilution technique is now widely used in the i-layer of a-Si solar cells. Considerable progress has been made concerning the increased stability of a-Si-based solar cells by proper device engineering. The general strategy is to use tandem or triple configurations. The establishment of a technical basis for a method of manufacturing low-cost, high-efficiency a-Si solar cells modules is a major part of R&D programs. In the Glass Substrate Program (Sanyo Electric Co. [4]), the highest stabilized efficiency of 9.5% has been achieved for an Si/a-SiGe tandem module with a size of 30 cm×40 cm using a high-quality a-SiGe i-layer by high hydrogen dilution at low substrate temperature. In this module, the deposition rate of the i-layer was around 0.1 nm/s. Now, the major issues are towards the development of manufacturing techniques of modules with a high deposition rate of 0.3–0.5 nm/s. Furthermore, as a low-cost patterning method, the plasma chemical vaporization machining (CVM) method has been proposed and 20-line patterning for an a-Si film with 40 cm length has been demonstrated.

There are also unique approaches such as flexible, see-through a-Si cell modules. In the Flexible Module Program (Fuji Electric Co. [5]), a stabilized aperture area efficiency of 9.0% has been obtained for a-SiGe/a-Si SCAF (Series Connection through Aperture formed on Film) cells.

A structure for a see-through a-Si solar cell has also been proposed [4]. For example, glass windows with see-through a-Si cell modules have been installed on a building of Hokuriku Electric Power Co. It is expected that a-Si cells will find wide application by using such unique characteristics.

3.3. CIGS and CdTe thin-film solar cells

CdTe is expected to be an ideal material for thin-film solar cells because it has a direct bandgap of 1.5 eV, well-matched to the terrestrial solar spectrum, and can be deposited with reasonable quality at a high deposition rate of around 10 μm/min. CdTe thin-film solar cells prepared by close space sublimation (CSS) techniques have attracted a significant scientific focus as low-cost solar cells. A manufacturing process for CdS/CdTe solar cells has been demonstrated [6]. The superstrate configuration — i.e., the glass/transparent conductive oxide (TCO)/CdS/CdTe/contact — is used for high-performance solar cells. CdTe solar cell modules with 10.6% efficiency for a medium-sized sub-module with an aperture area of 1376 cm^2, and 8.3% efficiency for a large sub-module with an aperture area of 5413 cm^2, have been fabricated by Matsushita Battery Co. A CdTe solar cell with 16% (1 cm^2) efficiency has also been successfully fabricated, consisting of ultrathin CdS and thin CdTe films.

A major issue with CdTe thin-film solar cells is still *p*-type doping and the formation of low-resistive ohmic contacts. CdTe cannot easily be doped *p*-type because of a strong self-compensation. Furthermore, the role of the intermixing layer at the CdS/CdTe interface should be clarified to obtain much higher open-circuit voltage (V_{oc}). There has been some concern about environmental and safety aspects connected with CdTe thin-film solar cells. In Japan these issues are currently under investigation. However, it is certain that strategies for end-of-life disposal or recycling of cadmium-containing modules will have to be developed in the future.

Chalcopyrite compound materials such as $CuInSe_2$ are attractive for PV device applications because their optical absorption coefficients are extraordinarily high, with measured values for $CuInSe_2$ being the highest reported among semiconductors, and they have shown very good stability. In order to increase the bandgap of the 1.02 eV $CuInSe_2$, gallium and sulfur are now commonly added to the compound semiconductor formulation. Typically, about 25–30% Ga is used, with an associated $Cu(In,Ga)Se_2$ (CIGS) bandgap near 1.15–1.20 eV.

Table 3 shows the major research and development targets for thin-film solar cells under the New Sunshine Program in Japan and the efficiency achievements [7]. In this program, the target of module cost was set by assuming an annual output of 100 MW_p/year in addition to the efficiency target of Si-based thin films. The R&D of CIGS solar cell technologies can be broadly divided into (1) developing volume production technologies of 30 cm square modules with an efficiency of over 13% that generate roughly 12 W of power, and (2) developing high-efficiency large-area cells with over 16% efficiency. The most remarkable improvement in CIGS thin-film solar cell efficiency has been the 18.5% efficient device achieved by Matsushita Electric Co.

3.4. Super high-efficiency III–V compound solar cells

The multi-junction configuration of 1.9 eV InGaP, 1.4 eV GaAs and 0.7 eV Ge, for example, has the possibility for realizing super high-efficiency of over 40% [8] due to wideband photo response.

Table 3
The major research and development targets for thin-film solar cells under the New Sunshine Program in Japan and the efficiency achievements

Solar cell material	Targets to be achieved by FY 2000	Efficiencies		Technical issues
		Small area (cm^2)	Large area (cm^2)	
a-Si-based thin film	η=10%, 140 JPY/W_p[a]			High-quality a-Si-based materials
	Glass substrate: 90 cm×90 cm	10.6 (1.0)	9.5 (1200)	Light-trapping structures
	Film substrate: 40 cm×80 cm		9.0 (3200)	High-speed patterning
				High-rate deposition of a-Si
Poly-Si thin film				
Plasma-CVD		10.7 (1.0)		Fabrication at low temperature
Zone-melting recrystallization	η=15%, 140 JPY/W_p[a]		16.0 (95.8)	Formation technology for high-quality poly-Si with high yield
	30 cm×30 cm		13.0 (961)	
a-Si/poly-Si stacked	η=14%, 5 cm×5 cm	12.0 (1.0)		Optical confinement
				Large-area deposition
Single-crystal Si thin film	η=14%, 5 cm×5 cm	12.5 (4.0)		Separation of large-area cell
				Reuse of Si substrates
				Enhancement of lifetime by gettering
CdTe thin film	η=13%, 140 JPY/W_p[a], 60 cm×90 cm	16.0 (1.0)	10.5 (1620)	Deposition at atmospheric pressure
				Low-cost deposition of CdS and TCO
CuInGaSe thin film				
Evaporation	η=16%, 10 cm×10 cm	18.5 (0.96)		Reducing amount of heavy metal
Selenization	η=13%, 140 JPY/W_p[a], 30 cm×30 cm		11.6 (864)	Improvement of Voc
				Zn-compound buffer

[a] For a production capacity of 100 MW_p/year.

As a result of improvements in tunnel junction and top cell performance, over 30% efficiency has been obtained with InGaP/GaAs two-juction tandem cells by Japan Energy Co. Fig. 9 shows a structure and *I–V* curve of the world-record efficiency InGaP/GaAs//InGaAs mechanical stacked three-junction solar cell. Efficiency of 33.3% has been attained with the mechanically stacked three-junction cell of an InGaP/GaAs two-junction cell and InGaAs bottom cell as a result of joint work by Japan Energy Co., Sumitomo Electric Co. and Toyota Technological Institute [9].

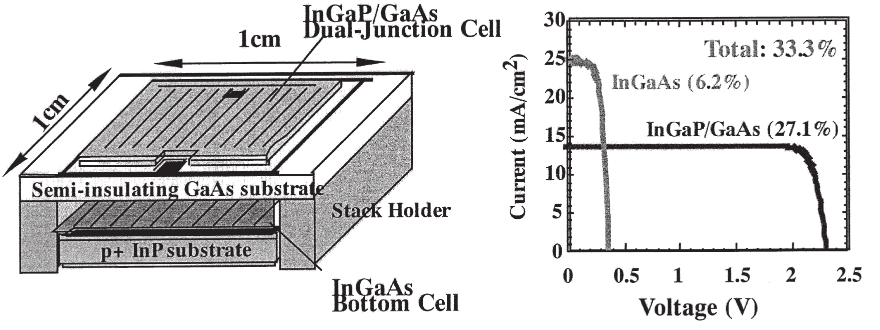


Fig. 9. Structure and *I–V* curve of the world-record efficiency InGaP/GaAs//InGaAs mechanical stacked three-junction solar cell.

Fig. 10 shows chronological improvements in conversion efficiencies of various solar cells fabricated in the laboratory. World-record efficiencies are 33.3% for the InGaP/GaAs//InGaAs three-junction tandem cell by Japan Energy Co., Sumitomo Electric Co. and Toyota Technological Institute; 25.7% for the GaAs single-junction cell by the National Renewable Energy Laboratory (NREL), USA; 24.7% for the single-crystal Si cell by the University New South Wales (UNSW), Australia; and 18.8% for the $CuInGaSe_2$ cell by NREL, USA.

InGaP/GaAs tandem cells have drawn increased attention for space applications because of the possibility of high conversion efficiency of over 30% and radiation resistance. In fact, because this type of cell has been put into commercial production for space use by TECSTAR Co. and Spectrolab Co., tandem solar cells are expected to be widely used for space applications in Japan.

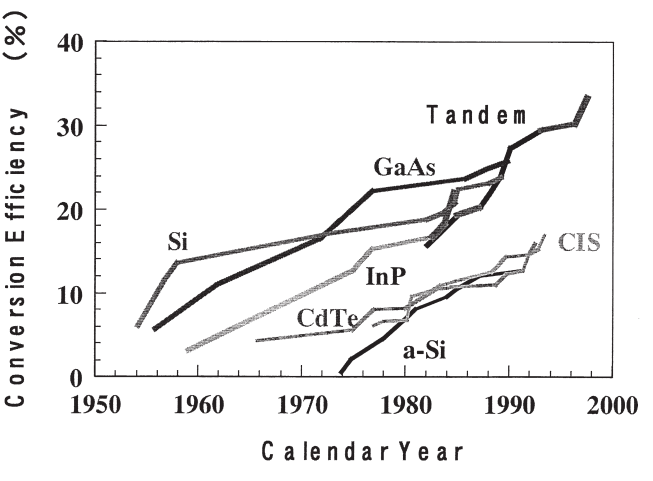


Fig. 10. Chronological improvements in conversion efficiencies of various solar cells fabricated in the laboratory.

4. Present status for manufacturing of solar cell modules in Japan

In this section, the present status for manufacturing of solar cell modules is presented.

Fig. 11 shows world solar cell module shipments [10]. The PV market continues to grow with global production of over 200 MW_p in 1999. The rapid growth of cell production occurred in Japan, USA and Europe. Especially, since 1994, Japanese production tended to increase rapidly. Last year (1999), Japanese solar cell module production was over 80 MW and attained No. 1 production. This remarkable increase in solar cell module production is mainly due to initiation of the government subsidy program for private PV houses. The number of Japanese PV houses installed in 1999 surpassed 18,000, corresponding to more than 60 MW_p.

Fig. 12 shows yearly world production of various types of solar cell [10]. The PV market increase depends upon a great expansion of cell production using polycrystalline and single-crystalline Si wafers. For film-type a-Si and CdTe solar cells, cell production had been almost constant, but it increased substantially for a-Si solar cells last year. As a whole, crystalline Si solar cells using bulk Si materials still dominate the current photovoltaic market for both remote and grid-connected power applications.

Fig. 13 shows world solar cell module shipments [10] in 1999. In 1999, Kyocera Co. and Sharp Co. produced 30 MW each and their production shares were 15%. Siemens Solar Co., Solarex Co. and Sanyo Electric Co. produced 22 MW, 18 MW and 13 MW, respectively, in 1999. Kaneka Co. announced the establishment of a 20 MW/year production line for a-Si solar cell modules and started production. In 2000, Kyocera Co. and Sharp Co. plan to produce crystalline Si cell modules with 60 MW/year each, and Mitsubishi Electric Co. plans to produce them with 12–15 MW/year. Also, Sanyo Electric Co. announced its intention to increase solar cell module production size to 120 MW/year by the year 2005.

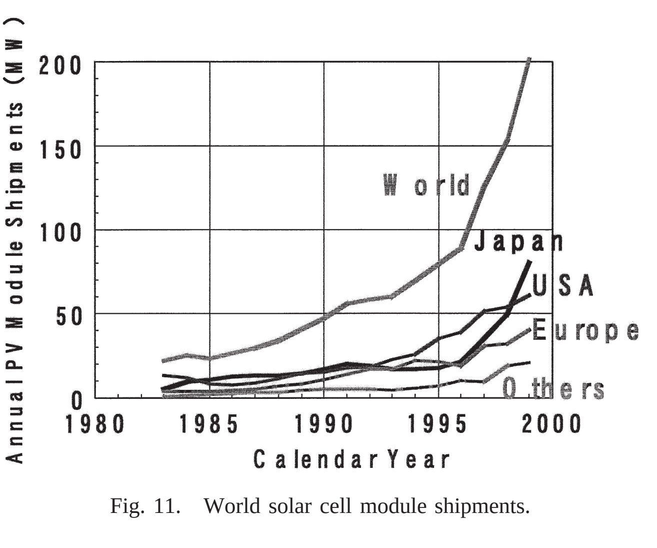


Fig. 11. World solar cell module shipments.

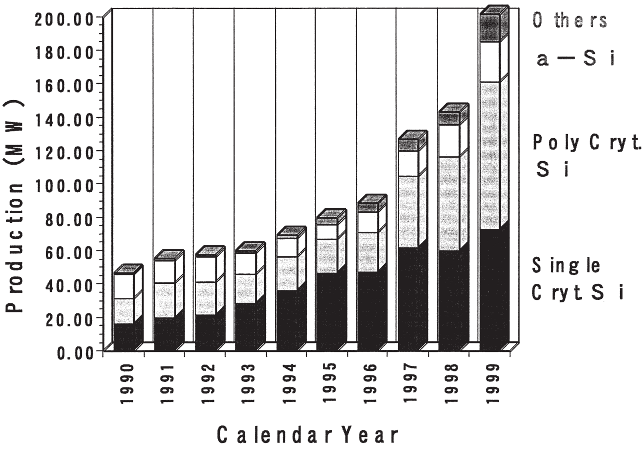


Fig. 12. Yearly world production of various types of solar cell.

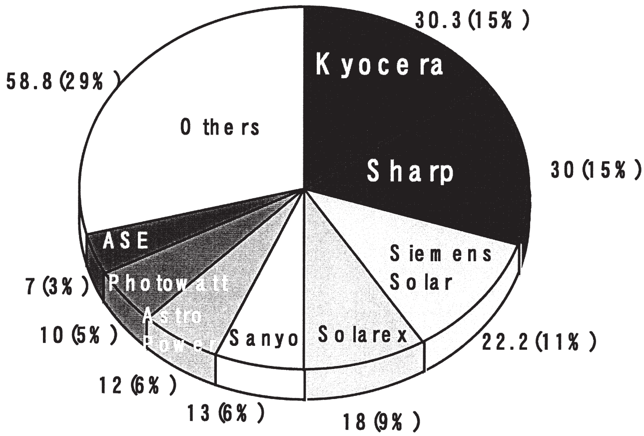


Fig. 13. World solar cell module shipments in 1999.

Fig. 5 shows changes in the price of 3 kW PV systems for residential houses in Japan [11]. The price of PV systems has decreased remarkably. The total price of a 3 kW_p PV system in 1994 was 6 million JPY and users had to pay 3 million JPY owing to the half subsidy. In 1998, the total price of the 3 kW_p system was about 3 million JPY and users had to pay 2 million JPY owing to the one-third subsidy. The cost allocation of the modules in the PV systems is about 60%.

Further cost reduction of solar cell modules and others is necessary in order to apply PV systems more widely.

5. Future prospects for photovoltaics

In this section, future prospects for PV power generation technologies, such as silicon material, thin-film and module technologies, concentrator systems and new application fields, are presented.

5.1. Si material technologies

Fig. 14 shows changes in demand for silicon materials for solar cell use in comparison with the production of crystalline silicon for use in integrated circuits (ICs). The major source for PV feedstock Si is the material “waste” that the electronics industry does not use. With rapid growth of the PV market, the availability of Si feedstock materials for solar cell use becomes uncertain. This means that the development of a low-cost feedstock for photovoltaics, solar-grade Si, is very important. Although the refining of metallurgical-grade Si materials is conducted in Japan [12], the development of a low-cost process and the scale-up of production size are problems.

5.2. Thin-film technologies

As expected, cost reduction of solar cell modules is a key factor for future cost reduction of PV systems. Fig. 15 shows the yearly reduction of the Japanese government solar cell module price, the so-called NEDO price, and also the government cost forecast under an assumed production of 100 MW_p/year. As indicated in the figure, the NEDO price is saturated to be about 600 JPY/W_p. One of the peculiar points in the figure is the existence of big cost gap between the current market price

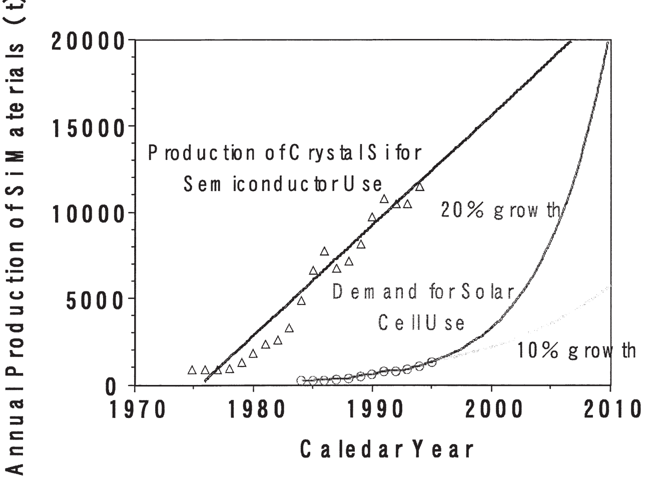


Fig. 14. Changes in Si material demands for solar cell use in comparison with the production of crystalline Si for IC use.

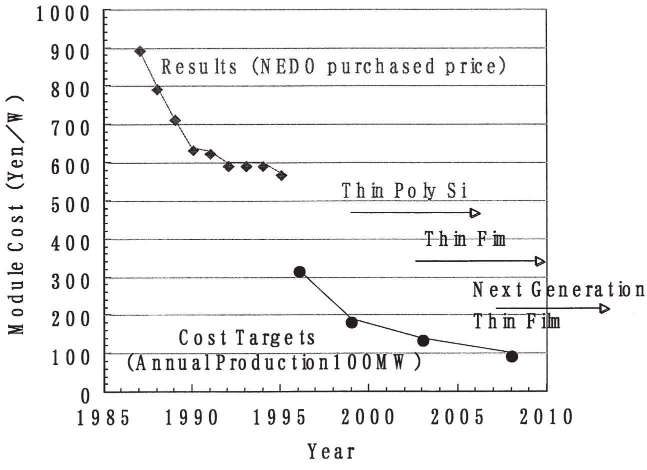


Fig. 15. Yearly reduction of the Japanese government solar cell module price, the so-called NEDO price, and also government cost forecast under an assumed production of 100 MW_p/year.

and the government cost forecast of 200 JPY/W_p. The development of low-cost solar cells such as thin poly-Si cells, thin-film cells such as a-Si cells, and next-generation thin-films solar cells is very important. In fact, greater production of thin-film solar cells than that of bulk crystal Si cells is expected after 2005 in Japan, as shown in Fig. 16 [13].

As a next-generation thin-film solar cell, the polycrystalline Si thin-film solar cell is expected. Fig. 17 shows the calculated conversion efficiency [14] versus film thickness for polycrystalline Si solar cells as a function of minority-carrier diffusion length. Realizing a high efficiency of above 15% is thought to be possible if a grain

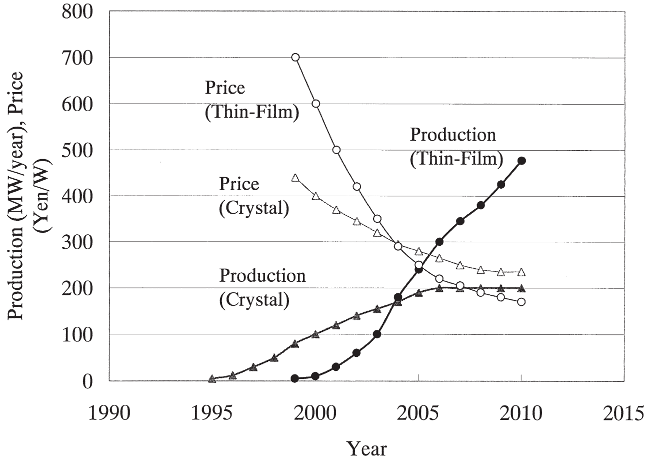


Fig. 16. Production scenario of thin-film solar cells and bulk crystal Si cells in Japan.

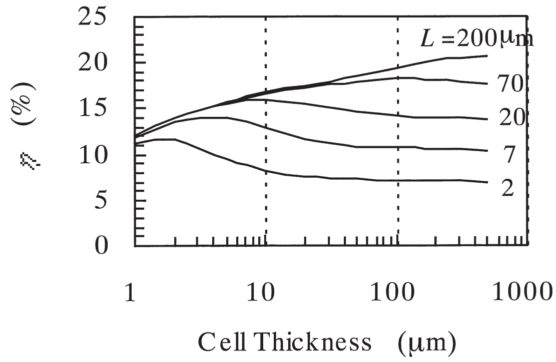


Fig. 17. The calculated conversion efficiency versus film thickness for polycrystalline Si solar cells as a function of minority-carrier diffusion length.

size of more than 10 μm is attained. Thin-film poly-Si solar cells with STAR (naturally Surface Texture and enhanced Absorption with back Reflector) structure — that is, optically confinement structure — has been proposed by Kaneka Co. [15]. Polycrystalline Si thin-film solar cells several μm in thickness have been deposited by plasma-assisted chemical vapor deposition (CVD) at low temperatures. The deposition of polycrystalline Si at low substrate temperatures is still a scientific challenge, but the polycrystalline Si thin-film cell with a thickness of 2.0 μm has already been demonstrated an intrinsic efficiency of 10.7%. A stabilized efficiency of 12.0% for a-Si/poly-Si/poly-Si three-stacked thin-film solar cells (1 cm^2) and that of 9.7% for a-Si/poly-Si tandem cell modules (30 cm×40 cm) have also been achieved.

5.3. Module technologies

Solar cell module technologies are also very important to reduce cost, to improve performance and to apply PV systems widely. There are several approaches for colorful, integrated and functional solar cell modules that customers may choose with their own preference.

5.4. Concentrator systems

Concentrator operation of the tandem cells is essential for their terrestrial applications. Since concentrator PV systems have the potential of cost reduction as shown in Fig. 18 [16], R&D on concentrator technologies including tandem cells should be started.

5.5. New application fields

Recently, thermophotovoltaics (TPV) have been received great attention [17]. Typical TPV systems include a radiation source such as the sun, combustion or a

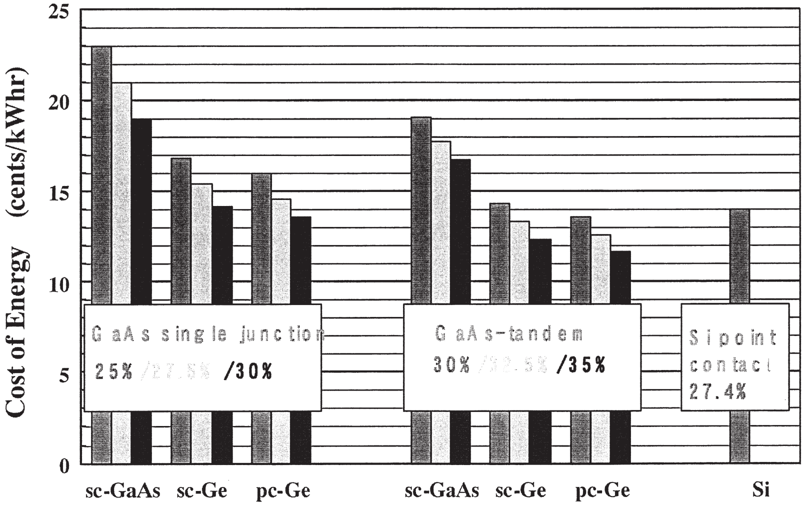


Fig. 18. Cost estimates and advantages for concentrator PV systems using various types of solar cell.

radioisotope, a selective emitter or filter, and a PV cell (converter). TPV systems have good characteristics such as clean co-generation, low maintenance costs, quietness, high power density outputs, and so forth. TPV systems have possibilities of widespread applications such as the use of industrial waste heat, in recreational and hybrid vehicles, in remote homes, stand-alone as furnaces, in military applications, etc.

The 100 W TPV co-generation system was already shipped last year. JX crystals have manufactured the Midnight Sun Stove [18] with heat generation of 25,000 BTU/h and electricity of 100 W, enough to operate a television. Fig. 19 shows a TPV system, made by a student in Toyota Technological Institute [19], that is composed of butane gas, Er_2O_3 selective emitter and GaSb cells, enough to operate a radio.

TPV technologies are not new but have possibilities of creating new application fields of PV.

6. Summary

In this paper, the present status of research, development and manufacturing for PV power generation systems has been reviewed. Especially, technologies of high-efficiency and low-cost crystalline Si, thin-film Si and Group II–VI compound solar cells and modules, and super high-efficiency III–V compound solar cells, have been presented. And Japanese government programs to promote solar houses — 18,000 PV systems were installed on Japanese houses in 1999 — have also been demonstrated. In addition, a variety of PV application systems have been shown. Future prospects of PV power generation technologies such as Si material, thin-film and



Fig. 19. A TPV system, made by a student in Toyota Technological Institute, that is composed of butane gas, Er_2O_3 selective emitter and GaSb cells, enough to operate a radio.

module technologies, concentrator systems and new application fields have been discussed.

Fig. 20 shows the milestone of annual PV installation in Japan. Fig. 21 shows the trend of production of solar cell modules and PV installation accumulated in Japan. It can be seen from the figure that the growth rate of Japanese PV installation and

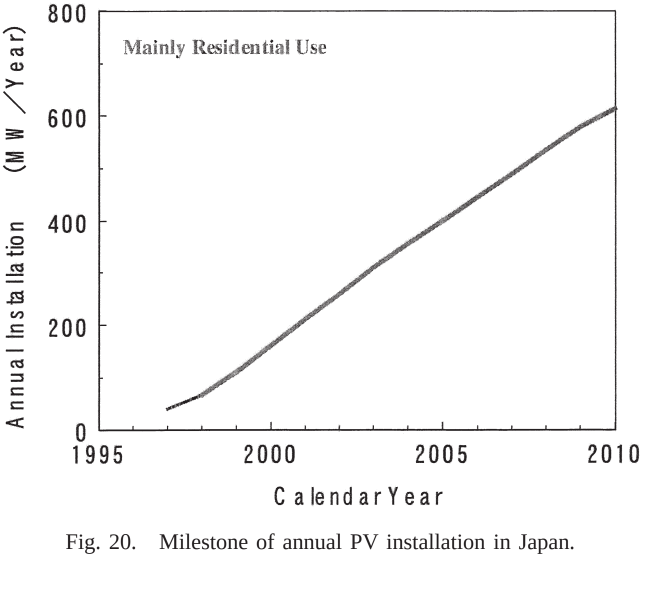


Fig. 20. Milestone of annual PV installation in Japan.

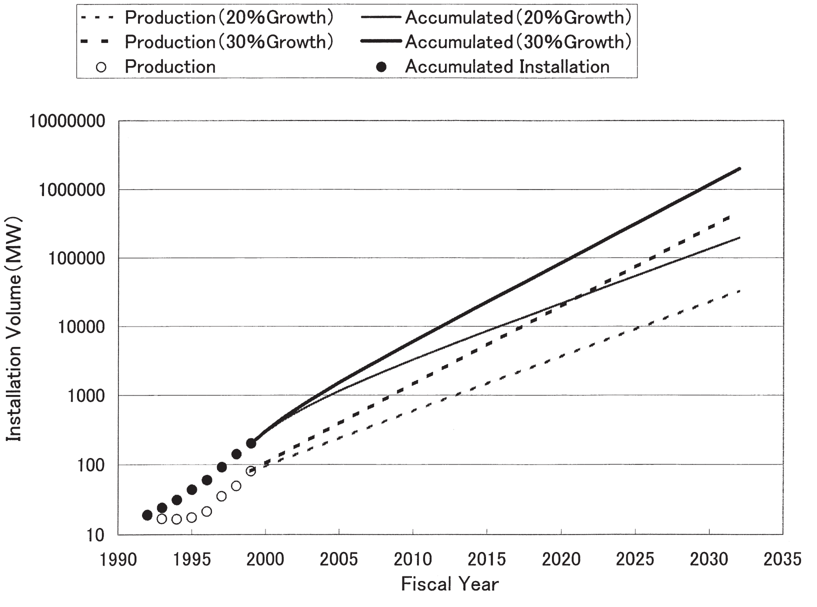


Fig. 21. The trend of production of solar cell modules and PV installation accumulated in Japan.

solar cell module production in recent years is 40~50%. In the cases of 30% and 20% growth rates, PV is expected to contribute to 10% of total energy in Japan by 2020 and 2030, respectively, even though utilization efficiency of PV systems is estimated at about 12%. Therefore, PV power generation systems are greatly expected to be applied widely and contribute to the future lives of human beings as one of the major clean energies based on advancements in the science and technology of photovoltaics and international co-operation.

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